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Blackbody effects in the Yb optical lattice clock

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Abstract—We report a high accuracy measurement of the differential static polarizability for the clock transition in a Yb lattice clock, a key parameter for determining the blackbody (BBR) shift of this transition. We further report efforts to determine the $\langle 6s5d^3D_1 || D || 6s6p^3P_0 \rangle$ reduced dipole matrix element, a critical ingredient in the non-static correction to the BBR shift. In all, we have reduced the largest uncertainty in the Yb lattice clock (that stemming from the BBR shift) by an order of magnitude.

I. INTRODUCTION

Optical lattice clocks have potential for achieving time and frequency measurement at unprecedented levels of accuracy and stability. The most recent evaluation of the ytterbium optical lattice clock at NIST yielded a fractional frequency uncertainty of 3.4×10^{-16} [1]. The largest contributor to this uncertainty was the Stark shift due to room temperature blackbody radiation, and represents a key obstacle which must be overcome to achieve 10^{-18} clock accuracy. The BBR shift can be written as [2], [3]:

$$\Delta\nu_{BBR} \approx -\frac{1}{2\hbar} \Delta\alpha^{(0)} \langle E^2 \rangle_T [1 + \eta_{clock}(T)] \quad (1)$$

Here, $\Delta\alpha^{(0)}$ is the differential static polarizability between the two clock states 1S_0 and 3P_0 (i.e. $\alpha_{3P_0}^{(0)} - \alpha_{1S_0}^{(0)}$). The static polarizability plays a prominent role in the BBR shift: because the room temperature BBR spectrum is concentrated at frequencies which are small compared to the energy difference of dipole-coupled atomic states, the atomic response to BBR is primarily a static one. $\langle E^2 \rangle_T$ denotes the time-averaged blackbody field bathing the atoms, which is parameterized by the characteristic temperature T (in this case, room temperature). Finally, because the BBR Stark effect is not a perfectly static one, $\eta_{clock}(T)$ gives the dynamic correction for the clock transition.

For the case of the Yb lattice clock, the BBR shift is $\Delta\nu_{BBR} \simeq 1.4$ Hz, or 2.5×10^{-15} [4]. The differential static polarizability $\Delta\alpha^{(0)}$ has been calculated at the 10% level [4], leading to a shift uncertainty of 2.5×10^{-16} . Furthermore, for the NIST Yb lattice clock, imprecise knowledge of the BBR environment bathing the atoms $\langle E^2 \rangle_T$ contributes a shift uncertainty of 3×10^{-17} . Finally, the dynamic correction is $\sim .01$ and is known at the 10% level, thus contributing a room temperature shift uncertainty of a few 10^{-18} . To reduce the room temperature BBR shift uncertainty from its

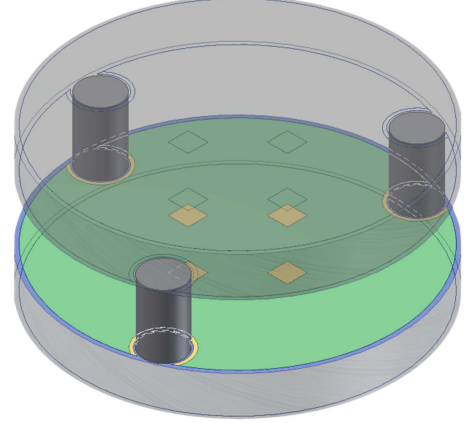


Fig. 1. Electrodes used for the Stark measurement. Upper and lower substrates (laser-grade fused-silica optical flats) are coated on the interior surface with a transparent, conductive ITO thin film shown in green. A set of three precision ground fused-silica spacers were KOH bonded to each electrode substrate, rigidly connecting the two electrodes. Each substrate had an additional deposition of four gold pads (in yellow) from which four distinct Fabry-Perot interferometers were formed, used to measure the electrode spacing.

previous level, a precise determination of the differential static polarizability must be made.

II. MEASUREMENT OF THE DIFFERENTIAL STATIC POLARIZABILITY

By applying a well-characterized, uniform static electric field to the atoms, measurement of the induced Stark shift on the clock transition leads directly to a determination of the differential static polarizability, i.e. $\Delta\alpha^{(0)} = -2\hbar\Delta\nu^{(0)}/E^2$. Such a measurement has been made previously with cesium atoms launched in an atomic fountain [5]. For our lattice-trapped atoms, one key consideration is to generate the electric field without precluding the optical access required for laser cooling and trapping in three dimensions. Thus, we fabricated the electrodes from optically transparent materials, as shown in Figure 1. Upper and lower electrodes used laser-grade fused-silica optical flats on which a thin film of indium tin oxide (ITO) was deposited, leaving an optically transparent, electrically-conductive inner surface on each substrate. The outer surfaces were anti-reflection coated. Three precision-ground fused silica spacers were bonded to fused silica blanks

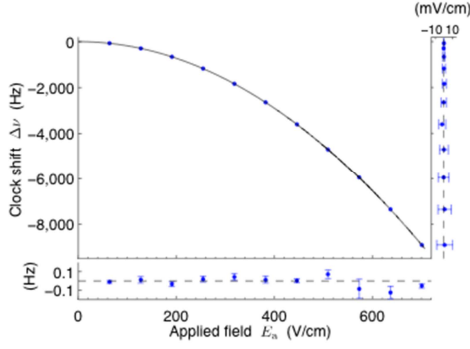


Fig. 2. Measurement of the induced Stark shift as a function of applied electric field. The polynomial fit is consistent with pure quadratic dependence, and is shown as the solid black curve with fit residuals to each side of the graph.

using hydroxide catalysis. These spacers created a rigid, uniform, and precise spacing between the electrode plates. Furthermore, four sets of gold pads were deposited on each electrode, forming 4 distinct Fabry-Perot interferometers with a finesse of 20 each. A laser scanned over tens of nm facilitated measurement of the free spectral range of each interferometer, and thus determination of the uniform electrode spacing, $d = 15.03686(8)$ mm. By applying high voltage (kV) to the electrodes, electric fields ($E = V/d$) approaching kV/cm were achieved, inducing Stark shifts of several kHz on the clock transition. By interleaving frequency measurements with and without the applied electric field, the shift could be determined to tens of mHz after 1000 s of averaging. Furthermore, by measuring the Stark shift with the electric field reversed, stray fields influencing the measurement could be characterized [6].

Measurements of the induced Stark shift are shown in Figure 2. For more information on this measurement, including further details of the experimental procedure and evaluation of the systematic effects, see [3]. Using the measured Stark shift, the differential static polarizability was measured to be $145.726(3)$ atomic units, with a stated accuracy of 19 ppm. We note that this polarizability measurement, one of the most accurate for any atomic or molecular system [7], agrees well with the ab-initio calculation made in [4], however with a reduction in the uncertainty by nearly four orders of magnitude. As a consequence, uncertainty in the static polarizability now contributes to a BBR shift uncertainty at a level below 10^{-19} . The total BBR uncertainty for the Yb lattice clock is now 3×10^{-17} , limited by knowledge of the BBR environment.

III. CONSTRAINING THE DYNAMIC CORRECTION

While the dynamic correction in Equation 1 is small, it cannot be ignored for room temperature operation of a lattice clock with 10^{-18} uncertainty. The dynamic correction for a given clock state a is defined in [2] as:

$$\eta_a = \frac{80/63\pi^2}{\alpha_a^{(0)} T} \sum_b \frac{|\langle b||D||a\rangle|^2}{(\omega_{ab}/T)^3} (1 + \dots) \quad (2)$$

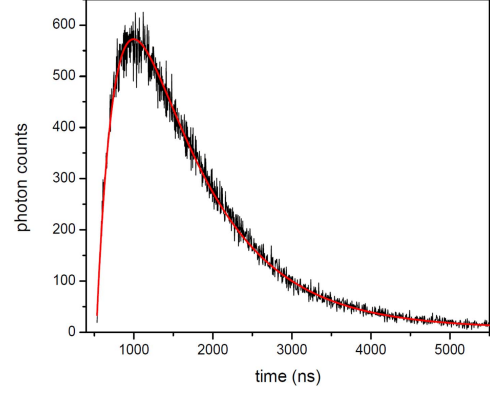


Fig. 3. Measurement of the 3D_1 lifetime via cascaded decay. A fitted function (red solid curve) extracts the measured lifetimes.

where b denotes the intermediate state to which a dipole coupling D is present, and $\hbar\omega_{ab}$ gives the energy separation between states a and b . An important point is the ω_{ab}^3 dependence in the denominator, strongly favoring contributions from states with a small energy separation. As a consequence, the largest contributor to the dynamic correction of the $6s6p\ ^3P_0$ clock state in Yb stems from the low-lying $6s5d\ ^3D_1$ state. This state accounts for more than 90% of the dynamic correction. However, the value of the reduced dipole matrix element $\langle 6s5d\ ^3D_1||D||6s6p\ ^3P_0\rangle$ is not well-known. An experimental determination based on a lifetime measurement [8] disagrees with the best theoretical calculation [4] beyond the 2.5σ uncertainty level. A determination of η at or below the 10% level requires improved knowledge of this matrix element. With this motivation, we have made several efforts to determine this matrix element. One such effort is shown in Figure 3, where atom population in 3D_1 experiences a cascaded decay to 3P_1 and then to 1S_0 . By monitoring fluorescence decay at 556 nm, corresponding to the $^3P_1\text{-}^1S_0$ decay path, the lifetime of 3D_1 can be measured, from which the reduced dipole matrix element can be deduced. We report a preliminary measurement of the 3D_1 lifetime of $335(20)$ ns. Ultimately, this measurement will be used to constrain η below the 10% level. For more details, please refer to an upcoming publication.

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